IN-44
192916
27P

DOE/NASA/50111-3
NASA TM-101470

Gas Turbine Alternative Fuels Combustion Characteristics

(NASA-TM-101470) GAS TURBINE ALTERNATIVE FUELS COMBUSTION CHARACTERISTICS Final Report (NASA) 27 p CSCI 21D
N89-21417
Unclas
G3/44 0192916

R. James Rollbuhler
National Aeronautics and Space Administration
Lewis Research Center

February 1989

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Transportation Systems

DOE/NASA/50111-3
NASA TM-101470

Gas Turbine Alternative Fuels Combustion Characteristics

R. James Rollbuhler
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

February 1989

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Transportation Systems
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-85CE50111

GAS TURBINE ALTERNATIVE FUELS COMBUSTION CHARACTERISTICS

R. James Rollbuhler
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-4584

SUMMARY

An experimental investigation, cosponsored by the Department of Energy and NASA, was conducted to obtain combustion performance and exhaust pollutant levels for specific synthetic hydrocarbon fuels. Performance was compared to baseline fuels. A flame tube combustor, simulating a gas turbine combustor, was used for testing. Each fuel was tested at steady-state operating conditions over a range of fuel to air mass ratios, mass flow rates, and inlet combustion air temperatures. The combustion pressure was kept relatively constant at two atmospheres for all tests.

Test results were obtained in terms of combustion and exhaust gas thermal capacities and the emission concentrations of oxygen, carbon dioxide, unburnt hydrocarbons, carbon monoxide, and nitrogen oxides. The fuels tested, with the exception of methanol, produced gas thermal loadings and emission concentrations similar to that of the base fuels: Gasoline and diesel #2 (DF2). The greatest variation in results was from changes in the operating parameters. The only detrimental factor observed was that at high operating temperatures heat soak back into the fuel nozzle resulted in the low hydrogen content fuels decomposing and causing nozzle passage blockage.

INTRODUCTION

An inherent advantage of any powerplant using a continuous combustion process, such as a gas turbine engine, is its capability of successfully burning a wide variety of fuels. By not needing fuels with narrow range specifications, such combustors should be capable of burning almost any kind of hydrocarbon fuel.

Since there is only a finite amount of crude oil stock in the world, eventually, irregardless of changing supply and demand and political perturbations, the supply could become so scarce as to constrain oil usage and implement alternative energy source fuels (ref. 1). Alternative fuels are generally considered to be fuels derived from coal, heavy crudes, tar sands, shale, or vegetable matter (ref. 2). These fuels come from sources that are readily available and will yield hydrocarbon type fuels which would closely resemble present fuels and present only a modest transition in combustion technology. Other substitute fuels, such as liquified methane or hydrogen, demand large investments in time and money for production, transportation, and powerplant storage and supply facilities. If the alternative fuels, such as those tested in this program, prove desirable, the world-wide distribution, storage, and handling techniques would be effected modestly from current practices.

The work of other investigators, e.g., Grobman (ref. 3), Hammond (ref. 4), Cohen (ref. 5), evaluated gas turbine combustors with alternate fuels at the two extreme operating conditions for aviation gas turbine engines; ground idle and take-off. At ground idle the engine is usually throttled back with minimum fuel flow through the combustor and, because of poor atomization, the combustion exhaust contains high concentrations of unburnt hydrocarbons and carbon monoxide. At takeoff conditions the engine is at maximum power and temperatures, pressures, and fuel flow are high. At these conditions unburnt hydrocarbons and carbon monoxide are much lower but nitrogen oxides become the major pollutant in the exhaust.

This program investigated the fuel combustion characteristics as a function of the combustion inlet gas temperature and the fuel to air mass flow ratio. The results reported are for a simplified test combustor. Therefore the absolute data values should not be expected to be the same for actual combustors. Rather the importance of the results is the relationship value of the results comparing one tested fuel to another and the trends as affected by the changing operating parameters. Data from other programs has been super imposed on some of the figures to show that the results are in accord with previous investigations.

ALTERNATIVE FUELS TESTED AND THEIR PROPERTIES

Eight fuels were tested in this program. All were supplied by Southwest Research Inc. under a contract from the U.S. Department of Energy. The fuels, and their important physical and chemical properties, are listed in table I. The gasoline and diesel #2 (DF2) fuels served as baseline references. The Exxon Donor Solvent (EDS) fuel was made from coal using a liquefaction process that utilized a recycle solvent flow through a catalyst reactor and hydrogenator. A detailed explanation of the process is contained in reference 6. The hydrogenated Exxon Donor Solvent (EDS) had extended hydrogenation with weight percent H_2 increased from 10.9 to 11.5. Several blends of petroleum base DF2 and EDS were also tested. Methanol was tested in the same test hardware as the other hydrocarbon fuels even though its peak performance could not be attained because of hardware restraints.

The most significant difference between these fuels is the increase in aromatic content of the coal base fuels and the decrease in the hydrogen concentration when compared to gasoline or DF2. The higher aromatic content results from utilization of a higher boiling point fuel that is produced at minimum cost. The cost of additional hydrogenization of the synthetic fuels to bring their hydrogen content up to that of gasoline is about three times the cost of producing the synthetic fuel in the first place (ref. 7). A consequence of lower acceptable hydrogen content, is higher carbon content. This can result in increased exhaust gas soot and accompanying radiation heat effects in the combustor.

ALTERNATIVE FUELS TESTED

Various fuel properties have a definite effect on how efficiently a given fuel will burn in a particular combustor at certain operating conditions. The reduced hydrogen content of a given fuel can also result in poor fuel atomization and vaporization. The relative burning time of a fuel droplet is 80 percent greater when it has a hydrogen content of 11 percent as compared to a fuel having a hydrogen content of 13 percent. If the hydrogen content is 12 percent, the burning time is 30 percent greater than at 13 percent. Another factor is the atomization of the fuel entering the combustor. A 50 μm gasoline droplet in a 2300 K environment takes 2.0 ms to burn; a heavy density diesel fuel droplet at the same conditions takes 3.5 ms to burn. Also droplet velocity through the combustor has an effect on the burning time; e.g., a 100 μm tar sands DF2 droplet burning time doubles in going from 1 to 75 m/sec. The most desirable properties, besides high hydrogen content, for a given fuel is low viscosity and surface tension so as to enhance atomization and droplet size (ref. 2).

Sutton, et al., has an interesting concept that the most important physical property of any fuel is its specific heat in regards to vaporization (ref. 14). The heating and evaporation of various fuels reveals that the rate of reaction with air is a function of the specific heat of the fuel. If the fuel specific heat increases, the liquid temperature rise is slowed such that the droplet evaporation slows. As the liquid drop temperature rises, the vapor concentration at the surface increases and a larger proportion of the heat transferred to the drop is used to supply the latent heat of vaporization. For example, Experimental Reference Broad Specification (ERBS) fuel specific heat is twice that of jet A at 588 K so the ERBS fuel droplet evaporation rate is negligible compared to the jet A.

THE TEST HARDWARE

The test combustor was a flame tube type that was modified to simulate a lean burn, advanced gas turbine engine combustor. The lean (minimum fuel) homogeneous combustible gas mixtures increase the combustor tolerance to low hydrogen content fuels by minimizing radiation heating from the high carbon content fuels (ref. 8). The combustor was operated at inlet combustion air temperatures, up to 1300 K, and at fuel to air mixture ratios, 0.005 to 0.025. A schematic drawing of the combustor is shown in figure 1.

A key factor in obtaining high performance with low hydrogen content fuels, is to achieve optimum atomization of the fuel and good mixing with the combustion air. A type of nozzle having this capability is the air blast design that incorporates a pitot air flow through the nozzle to shear the injected fuel streams. A CF6-50 combustor having an air blast fuel atomizing nozzle was able to reduce the radiation heat load to the combustor walls by 50 percent compared to a conventional nozzle operating at the same conditions (ref. 9). Also an air blast nozzle operating at the same conditions as a simplex fuel nozzle resulted in a noticeable reduction in soot production (ref. 5). In the test combustor approximately 2 to 3 percent of the combustion air flow was injected through the fuel nozzle. The air pressure drop was kept high for maximum momentum and the nozzle fuel to air mass ratio was 0.1 to 0.2. Prior work indicated that combustion efficiency is improved and nitrogen oxide formation

is reduced if the primary or initial mixture ratio is in the 0.11 to 0.14 fuel to air region (ref. 10).

The nozzle was located in the upstream end of the combustor and was isolated from the hot combustion air flowing around it. However, heat soak-back during testing occurred through the combustor-nozzle connection. The nozzle spray was directed into a combustion cup surrounding the nozzle exit and enough of the combustion air was directed into the cup to attain a stoichiometric fuel-air mixture that was then ignited using a high energy spark probe.

The ignited stoichiometric gas mixture then flowed into the combustor primary zone along with the remaining combustion air flowing in a swirl pattern around the ignited gases. Based on Garrett Company studies (ref. 8), approximately half the combustion air was used in this final mixing operation. The final mixture ratio of fuel to air being the one reported in the results. The transition of gas flows minimizes the gas recirculation zone, but the change in velocities enhances the fuel and air mixing.

THE TEST COMBUSTOR

The combustor was a 7.6 cm diameter stainless steel tube approximately 45 cm long. The diameter and length were sized such that the combustion gas residence time was 4 to 8 ms and the gas velocity was 30 to 120 m/sec, depending on the mass flowrate and temperature. It is believed that the fuel droplet vaporization and burning is a function of its initial injection size and its residence time. Therefore the combustion efficiency based on the combustion gas average temperature reported previously (ref. 11), is not so much fuel to air mixture ratio or gas phase reaction favored as it is in the time the fuel droplet required to go from a liquid to a mixed gas that can react (ref. 5). Two different air blast fuel injection nozzles were used. These nozzles, in schematic layout, are shown in figure 2. The initial nozzle is labeled P-A and the final usage nozzle is labeled C-A. Both had similar fuel atomization behavior over the test conditions. The P-A nozzle encountered problems in that thermal soak-back caused fuel decomposition or breakdown in its narrow confining fuel flow passages and with time, the deposits built up enough to change flow characteristics and pattern factor (see ref. 11). The P-A nozzle was impossible to disassemble and clean. The C-A nozzle also has small passages that were subject to deposition, but was made so that it can could be disassembled between test runs and cleaned.

THE TEST FACILITY

Program testing was conducted in the Combustion Research Test Facility (cell 23) at the NASA Lewis Research Center. The Facility has the capability of supplying inlet combustion air (up to 1 kg/sec and up to 1250 K) for extended periods. This feature simulates conditions that would occur in a regenerative gas turbine engine, or one that had a high compression ratio. A schematic of the facility is shown in figure 3. The inlet combustion air is heated by flowing it through a hot, porous ceramic wheel. The unvitiated hot air is then supplied to the combustor. This wheel is heated by a burner on one side, and as the wheel rotates past flexure seals that separate the burner gases from the combustion air, it releases its heat to the flow-through air

stream. The air temperature is controlled by the wheel rotation rate and the burner hot gas temperature and flowrate. The combustion air and exhaust gas pressure was regulated by a downstream pressure control valve. The combustion gas pressure for all the tests was approximately two atmospheres.

TEST RIG INSTRUMENTATION

Data acquisition was accomplished by obtaining continuous measurements of the fuel injection pressure, temperature, and flowrate; the combustion air injection pressure, temperature, and flowrate; and the combustion and exhaust gases pressures and temperatures. The measurements were selectively recorded for later processing. The instrumentation was calibrated prior to each test run.

The fuel flowrates were determined from dual liquid mass flowmeters. The air flowrate was measured using orifice and pitot tube type flowmeters. Type K thermocouples were used to measure the low temperatures and type R thermocouples measured high temperature conditions The pressures were measured with strain-gage type transducers. For the combustion air upstream of the combustor, the combustion gas, and the exhaust gas, the reported temperature for each is an average of twelve circumferentially spaced thermocouple readings at each location. If one or more thermocouples failed during a test, the average was based on the remaining active thermocouples at that particular location.

The combustion gas was sampled continuously during tests from a location at the exit of the test combustor. The sampling probe was water jacketed to keep it intact in the hot gas stream. Sample gases under pressure flowed through it and connecting lines to the control room analyzers 18 m away. The gas sampling line was heated above the dew point temperature of the sample gases flowing through it.

The gas analyzers were calibrated prior to each day of testing with gases of known pollutant concentrations. Based on these calibrations, and the sampling procedures, it is felt that the gas analysis is within ±2 percent of true concentration. The unburnt hydrocarbons from the combustor were measured using a Beckman model 402 flame ionization detector. Beckman model 315B nondispersive infrared units determined the level of carbon monoxide and carbon dioxide. The nitrogen oxides were determined using a Thermo-Electron chemiluminescent type model 10A. Oxygen concentrations were determined by a Beckman model OM-11 analyzer. A Thermo-Electron Model 40 sulfur dioxide pulsed florescent analyzer and a Berkeley model 107 opacity meter for soot or carbon in the gases were also in the emissions measuring system but detected only trace levels of these emission pollution during the testing.

TEST OPERATIONS

The program test plan was to evaluate each of the fuels in turn according to a matrix test pattern. Test parameters were the combustion air flowrate, the combustion air temperature, and the fuel to air mass ratio. Fuel temperature were ambient going into the test rig and the combustion gas pressure was maintained at approximately two atmospheres. The test matrix is shown in table 2. The maximum airflow of 0.45 kg/sec was the maximum which could be

consistently obtained; the minimum airflow tested was 0.1 kg/sec. The maximum air inlet temperature was 1090 K in order to keep the combustion gas temperature at about 1360 K or less so as not to damage the gas stream thermocouples. The fuel to air ratio test range was kept on the lean side of stoichiometric conditions because it has been previously shown that such mixtures increase the combustion tolerance to low hydrogen containing fuels and keep carbon formation or sooting at a low level (ref. 12). Scheduled were 72 tests for each fuel or a total of 576 for the 8 fuels tested.

Each test was carried out at a discrete air flow and temperature and fuel to air ratio until it could be verified that the input parameters and the test data were at steady-state conditions. This usually occurred within 3 to 4 min. The air flow was first introduced and when temperatures were stable, the fuel was injected. About every 30 to 60 sec test data were recorded. For each test condition, three or four readings were taken. Usually the last reading of each test was the one used for reporting.

The air and fuel flowrates obtained during the testing were as much as 15 percent in variance from what is shown in matrix pattern. This was due to operational difficulties. But once a flowrate was selected, the set up controls could hold it within ±4 percent for a given flow condition. Variance also occurred for the input air temperature. The facility operator could achieve within ±25 K of what was requested. However, when a value was obtained, it could be held at that value within ±10 K during the test. The test steady-state conditions were judged to be attained when the output gases did not vary more than ±10 K.

DISCUSSION OF RESULTS

Program results are presented as a function of the fuel to air mass ratio. In order to simplify the reported results, a flow of approximately 0.3 kg of air per second was arbitrarily selected as being representative. Two input air temperatures approximately 810 and 1090 K were selected: the former simulating idle engine operating conditions; the latter simulating maximum power conditions. Even with these selective values, test plots of data points made a confusing figure, especially where so many fuels had similar results. Therefore, shown in the figures are median lines which were drawn through multiple test points of three or more. The deviation from the median lines is about ±2 percent on the thermal plots and about ±5 percent on the emission plots. The median result lines are meant to show trends at particular operating conditions and to give a general comparison of results for different fuels. The results are in the same general regime as those furnished by other investigators, some of which are also included on the figures.

DISCUSSION OF RESULTS: COMBUSTION PERFORMANCE

The function of the gas turbine combustor is to produce combustion gases having the maximum energy value per unit volume that can be used to power the gas turbine drive system, and to produce engine thrust. This program simulated these operations by determining the combustion gas temperatures and thermal loading as a function of the combustor inlet air temperature and the fuel to air mass ratio. The theoretical combustion gas temperature and gas energy

level (the enthalpy) were determined for each of the test fuels using analytical techniques developed by Gordon (ref. 21) and calculated by McBride (ref. 22).

Since the facility check out testing was done using gasoline as the fuel, it was decided to use that as the baseline for comparison with the other fuels. The performance reported is that obtained at an inlet mass flowrate of approximately 300 g/sec and, at air temperatures of approximately 830 and 1090 K.

The gasoline test data thermal energy level, both theoretically and from testing, is presented in figure 4. The experimental thermal energy was determined from the combustion gas average temperature as well as the measured heat losses through the combustor wall; both calculated from thermocouple data. At the 830 K level the test data gave an efficiency ranging from 107 to 91 percent of theoretical over the tested F/A range. At the 1090 K level the test efficiency ranged from 97 to 99 percent of theoretical. The test data were at inlet gas temperatures that were within ±25 K of the stated levels.

The theoretical and output enthalpy values for the gasoline and the other fuels tested is presented in figure 5 as a bar graph. White bars are the theoretical value for each fuel and shaded bars are the test data values. The left side of each bar is the enthalpy value at a F/A value of 0.01 and the right side of the bar is the enthalpy value at a F/A value of 0.02. The theoretical values were calculated by McBride for each fuel (ref. 22). All the fuels were tested at the higher inlet temperature (approximately 1090 K) but enough data for reportable results at 830 K inlet conditions, was obtained with gasoline, E.D.S., and hydrogenated E.D.S. fuels. The theoretical enthalpy decreases with increasing F/A because more energy is required to vaporize and heat the additional fuel up to the reaction temperature. For some of the fuels this trend held for test results and for others just the opposite occurred. For these fuels low F/A vaporization and reactions efficiency restricted the attainable combustion gas energy level.

Another comparison of performance is the increase in combustion gas temperature within the combustor. The increase is set as the difference between the combustion gas average temperature and the inlet air temperature. From figure 4, gasoline test data, it can be seen that at 830 K inlet conditions this temperature difference was about 360 K at a F/A = 0.01 and 610 K at a F/A = 0.02. At a 1090 K inlet condition the temperature difference was 290 K at a 0.01 F/A and 590 K at 0.02 F/A. Assuming these values are baseline data, then the temperature differentials obtained at the identical test conditions with the other fuels can be compared to the gasoline data. This has been done in figure 6 where each fuel is again shown as a bar graph. The left side of each bar is data at 0.01 F/A and the right side of each bar is data at 0.02 F/A. The value of each bar is a percentage of that fuels temperature differential in relation to that obtained with gasoline. Gasoline is shown as 100 percent for both 830 and 1090 K inlet conditions. For the most part all the other fuels had temperature rises that were greater than that obtained with gasoline, the exception being methanol which is presented at a F/A range that is an extreme of its normal operating range. The temperature increase was especially significant for most of the fuels at the higher F/A values.

The energy level of the combustion gases was similar over the range of conditions tested. The fuel nozzle seemed capable of atomizing the fuels sufficiently to induce mixing and reaction that would produce efficiencies in the 90 percent region. The fuels, except for the methanol, produced sharp temperature rise in the gas, over 600 K as compared to 500 K for gasoline at the high F/A values.

The results obtained with a given fuel may not be the same if used in different combustor with a dissimilar fuel nozzle, but they are in the same regime of combustion temperatures as reported by others. Kaufman (ref. 13) in tests with a JT8D combustor obtained similar temperature increases over this same F/A range when using Jet A fuel. His temperature rise efficiency was 87 percent at a 0.015 F/A. Norgren (ref. 16) obtained temperature rise efficiencies varying from 50 percent at 0.01 F/A to 110 percent at 0.03 F/A, chiefly due to what fuel flowrate atomization the fuel injector is optimized for. This particular combustor and nozzle were patterned after a Garrett Company design and Sanborn (ref. 8) reported a gas temperature rise of 400 K at 0.009 F/A and 1240 K inlet air temperatures with the Garrett designed unit.

DISCUSSION OF RESULTS: OXYGEN EMISSIONS IN THE COMBUSTION GASES

The measured volume percent of oxygen (O_2) in the combustion gases for each of the fuels tested as a function of the F/A is shown in figure 7. During the testing the percent O_2 was used as a guide as to the combustion efficiency. As was mentioned in this program's previous report (ref. 11), the theoretical oxygen concentration for hydrocarbons burning at these F/A has the same depletion slope as the presented results show but the values fall between the tar sands DF2 and the EDS fuel median value lines.

This would indicate that while combustion is completed for the tar sand DF2 and the DF2-EDS blends, it is incomplete for the other fuels. They have excess oxygen which had not reacted with the fuel by the time the gases reached the combustor gas sample point. If oxygen concentrations had been measured at the site where the exhaust gas was hotter than the combustion gas, the results might be closer to the theoretical line, but all sampling was done at the same location downstream of the combustor.

The methanol testing used the least amount of oxygen in the combustion air, probably because the testing was done at conditions so far from stoichiometric F/A (0.156 versus 0.068 for the other hydrocarbons). The methanol BTU content of only 8570 units per pound, compared to 17 800 to 18 300 for the other tested fuels, results in an unfavorable showing at the low fuel to air ratios used in this program.

DISCUSSION OF RESULTS: CARBON DIOXIDE EMISSIONS IN THE COMBUSTION GAS

The measured volume percent of carbon dioxide (CO_2) in the combustion gases for each of the fuels is shown in figure 8 as a function of the F/A. The results indicate similar trends as has been described for the oxygen concentration. The CO_2 levels are opposite the O_2 levels for the same fuel; that is, the CO_2 level is highest for those fuels which had the smallest O_2 level. This being an indication of most of the oxygen being combined with fuel carbon resulting in complete oxidation to CO_2. It was shown in the programs previous

report (ref. 11) that the theoretical line is between the tar sands DF2 and the gasoline results, and that the data produced approximately the same slope with changing F/A. Again the tar sand DF2 and the DF2-EDS blends apparently had enough time to react within the combustor to produce an equilibrium amount of carbon dioxide whereas the other fuels shown did not have enough time to fully react with the carbon. The least reactive being the methanol fuel which produced minimum carbon dioxide. At the selected test conditions, the heat generated by the methanol and air reaction was probably too little to further oxidize the carbon monoxide produced into carbon dioxide.

DISCUSSION OF RESULTS: UNBURNED HYDROCARBONS AND SOOT EMISSIONS

The measured concentration of unreacted hydrocarbons (UHC) in the combustion gas for each of the fuels as a function of the F/A is presented in figure 9. The concentration is expressed as an emission index valve (UHCEI), that is, grams of equivalent methane per kilogram of fuel expended.

For most of the fuels tested, the UHCEI was very low, less than two, over the F/A range tested. Exceptions were the hydrogenated EDS and the methanol fuel. The methanol fuel having a high UHCEI at these test conditions is understandable what with being so far from the stochiometric F/A, but why the hydrogenated EDS has a high UHCEI (and low CO_2) and a high combustion temperature is not clear.

The test results follow the same pattern as other investigators have found - as the F/A is increased from idle power conditions (approximately 0.01 F/A) to full power conditions (approximately. 0.02 F/A), the UHCEI rapidly drops off. For example, Cohen in testing a T700/CT7 jet A fueled engine, recorded a ground idle UHCEI of 4.5 and a maximum power UHCEF = 0.5 (ref. 5). Grobman reported an UHCEI = 18 at idle conditions, and less than 5 at full power with a JT8D engine. When he used a standard fuel nozzle he realized an UHCEI of 12 at a F/A = 0.015 and when he used an air assist nozzle he recorded 2 at F/A = 0.015 (ref. 3).

Fletcher reports getting UHCEI = 9 at 477 K inlet air temperature, 0.15 at 588 K, 0.08 at 699 K, and 0.02 at 811 K (ref. 15). Sutton made tests using Jet A and DF2 fuels; at a F/A = 0.022 the Jet A UHCEI was 0.26 and with DF2 was 46.3, at a F/A = 0.010 the jet A UHCEI was 70.2 and with DF2 it was 174 (ref. 14). Norgren showed in his testing with Jet A that the combustion pressure ratio had an effect. At a pressure ratio of three the UHCEI = 500, when the ratio was increased to six the UHCEI = 150, and when there ratio was greater than nine, the UHCEI = 1 (ref. 16). Tien and Anderson pointed out how rapidly UHCEI changed as the combustion gases traveled down a duct: at a reference location the UHCEI = 100 (F/A = 0.015), 7 cm downstream of this location the UHCEI was eight, and 22 cm downstream of the location the UHCEI was 0.5 (ref. 17).

During this test program an opacity measuring analyzer, looking across the exhaust gas stream, was used to determine if the opacity was changing due to smoke or soot in the stream. The analyzer did not indicate any measurable smoke or dense particles in the stream. After testing for over 100 hr the interior of the combustion was examined and only a micron thickness of soot was apparent around the fuel atomizing nozzle; the remainder of the combustor interiors was soot free.

DISCUSSION OF RESULTS: CARBON MONOXIDE EMISSIONS IN THE COMBUSTION GASES

The measured concentrations of carbon monoxide (CO) in the combustion gases is shown in figure 10 for each of the fuels tested as a function of the F/A. The concentration is expressed as the grams of CO produced per 1000 g of fuel reacted (CO EI).

Most of the fuels had median COEI levels that were less than 50 and did not deviate much from that level over the F/A range tested. The DF2 + EDS blends, the gasoline, and the two DF2's were less than 30 COEI. The high COEI valves for the methanol fuel tests was expected at these F/A values for the same reasons as expressed for the high UHCEI levels. The high levels for the EDS fuels, especially the hydrogenated EDS, would not be expected at the high combustion gas temperatures that were measured (fig. 5). Since the hydrocarbon concentration was also higher than average, it might be assumed that the high temperature recorded was in part due to radiation effects.

The usual trend for CO emissions is for their concentration to decrease with increased F/A and then increase at higher F/A values. The high level of CO at low F/A values is due to slow oxidation rates of carbon associated with low combustion temperatures. Increases in F/A values raise the flame temperature which accelerates oxidation of C to CO to CO_2. At temperatures above 1700 K (i.e., high F/A values), the CO starts to increase again as the CO_2 dissociates. Increasing combustion air inlet temperatures promote this increase in CO_2 dissociation. The oxidation of the C and CO to CO_2 is encouraged by the fuel being atomized into very small droplets (ref. 18).

Superimposed on the results obtained in this program, are results obtained by other investigators. Those labeled "N" are from work done by Norgren and Riddlebaugh (ref. 19) using Jet A fuel, those labeled "T" are from work reported by Sutton, Troth, and Miles (ref. 14) using Jet A and DF2 fuels, that labeled "K" is from the work of Kauffman (ref. 13) using JP4, and the "G" data are from a Grobman report (ref. 3). They show a decreasing of COEI with increasing F/A in the general concentration area that this program found for COEI valves.

Generally, both the UHCEI and COEI valves decrease at the same F/A valves but the UHCEI do not start increasing at higher F/A induced flame temperatures, as does the COEI as the carbon emissions go from CO_2 back to CO.

DISCUSSION OF RESULTS: NITROGEN OXIDE EMISSIONS IN THE COMBUSTION GASES

The measured concentration of nitrogen oxides (NO_x) in the combustion gas stream is expressed as an emissions index (NOXEI). The index is the grams of NO_x produced per 1000 g of fuel burned. Test results are contained in figure 11 for each fuel as a function of the F/A test range.

Since there are minimal nitrogen compounds in the tested fuels, the NO_x formed is almost entirely from thermal oxidation of the nitrogen in the combustion air. As the F/A increases the flame temperature increases and more of the flowthrough nitrogen is oxidized. This is presented in figure 12 where the NOXEI is plotted as a function of the combustion gas average temperature. This trend is apparent for all the fuels shown in figure 11; some more so than others. The tests at the idle condition input air temperatures produced about

a third as much NOXEI as did the same fuels when using the maximum power input air. The gasoline and diesel fuels produced the most NOXEI at any given F/A, the DF2-EDS a little less and the EDS fuels the least amount. At the very bottom are the methanol fuel tests which did not produce much NO_x because of their relatively low operating temperature conditions.

Shown also in figure 11 are NOXEI results obtained by other investigators. The work of Norgren (refs. 16 and 19) is labeled "N." The NOXEI from Jet A and DF2 as obtained by Sutton (ref. 14) is labeled "T." Miscellaneous data from Hammond (ref. 4), and Grobman (ref. 3), are labeled "H," and "G," respectively. The values obtained in these commercial engine combustor tests are of a similar magnitude as this program NOXEI valves. The rate of increase may be different due to different fuel spray nozzles used for testing.

The largest values of NOXEI, at the maximum power operating conditions, were with gasoline and the petroleum base DF2 fuels. The syn fuels (i.e., those obtained from nonpetroleum sources) gave lower value NOXEI values at the same combustion temperatures than the gasoline and DF2.

A general rule, stated in the literature, is that as the inlet combustion air temperature increases by 400 K (e.g., 400 to 800 K), the NOXEI will increase by a factor of 10 (ref. 15). Likewise, as the reaction temperature goes from 1750 to 2650 K, the NOXEI will multiply by a factor of 100 (ref. 2). Spadaccini in his testing at high F/A's, found that increasing the combustion pressure also increased the NOXEI level (ref. 20) but Norgren has reported (ref. 16) that at high pressure ratios and low F/A the NOXEI is less than at lower pressure ratios.

SUMMARY OF RESULTS

The results in this program show the relative comparison of combustion gas emissions for selective alternative hydrocarbon fuels as compared to baseline fuels such as gasoline and petroleum based diesel fuel. The emission evolvement as a function of the input combustion air temperature and the fuel to air mass ratio is also presented. Caution should be taken in regard to the actual emission values stated; they are presented for comparison only to relate the various fuels tested at the given test conditions stated in this report. But the magnitude of the results presented is in the same order as that shown by other investigators.

Using an air blast fuel spray nozzle, a three-stage combustion process, and high inlet air temperatures, all the fuels could be atomized and ignited in the specified test conditions. The combustion temperatures obtained were not as high as desired as the different fuels probably had different physical properties preventing complete vaporization in the given combustor. Sutton (ref. 14) who also used an air blast nozzle in his combustor, concluded that the fuel thermal properties (e.g., heat of combustion) are a minimal consideration in obtaining combustion efficiency as compared to the physical (vaporization) properties. In regard to emissions, the ideal situation is to control the combustion gas temperature so as to allow enough residence time for the consumption of the hydrocarbons and carbon monoxide but keep the temperature low enough as not to generate excess nitrogen oxides. Also a factor reported by others is the reduction of emissions by using high combustor pressure ratios (at low F/A's).

This program has shown that to get high performance (i.e., high flame temperature) and minimum emissions comparable to gasoline or diesel fuel, a good choice might be an alternate fuel composed of DF2 and EDS. The blends tested in this program had combustion gas temperatures similar or higher than that obtained with gasoline at the same test conditions, and the key emissions, CO and NO_x, at many test conditions were less than what were obtained with gasoline fuel. None of the fuels tested were extremely poor in combustion characteristics or emission production except the methanol which was being compared at a very low equivalence ratio and has a much lower chemical heat content than the other tested fuels.

REFERENCES

1. Grobman, J.; and Longwell, J.P.: Alternative Aircraft Fuels. J. Eng. Power, vol. 101, no. 1, Jan. 1979, pp. 155-161.

2. Odgers, J.; and Kretschmer, D.: Gas Turbine Fuels and Their Influence on Combustion. Abacus Press Co., 1986.

3. Grobman, J.: Effect of Operating Variables on Pollutant Emissions from Aircraft Turbine Engine Combustors. NASA TM X-67887, 1971.

4. Hammond, D.C., Jr.: Operation of a GT-225 Diffusion-Flame Combustor on Alternative Fuels Performance, Durability and Emissions. ASME Paper 79-GT-138, Mar. 1979.

5. Cohen, J.D.: Analytical Fuel Property Effects on Small Combustors. (R82AEB078, General Electric Co.; NASA Contract NAS3-22829) NASA CR-168138, 1983.

6. Schultz, D.F.: Summary of Synfuel Characterization and Combustion Studies. NASA TM-83066, DOE/NASA/13111-15, 1983.

7. Uyehara, O.A.: Transportation Fuels - 1978 Crude Oil Scene. Composition of Transportation Synfuels: R&D Needs, Strategies and Actions, DOE CONF-7810176, 1979, pp. 219-252.

8. Sanborn, J.W.; Mongia, H.C.; and Kidwell, J.R.: Design of a Low-Emission Combustor for an Automotive Gas Turbine. AIAA Paper 83-0338, Jan. 1983.

9. Cairelli, J.; and Horvath, D.: Compatibility of Alternative Fuels with Advanced Automotive Gas Turbine and Stirling Engines - A Literature Survey. NASA TM-81754, 1981.

10. Furman, E.R., et al.: Critical Research and Advanced Technology (CRT) Support Project. NASA TM-83019, DOE/NASA/10350-35, 1983.

11. Rollbuhler, R.J.: Combustion Characteristics of Gas Turbine Alternative Fuels. NASA TM-100247, DOE/NASA/50111-1, 1987.

12. Blazowski, W.S.: Fundamental Characterization of Alternate Fuel Effects in Continous Combustion Systems - Technical Progress Report No. 1. Exxon Research and Engineering Co., TID-28463, Jan. 1978.

13. Kauffman, C.W.: Effect of Ambient Conditions on the Emissions from a Gas Turbine Combustor. NASA CR-3355, 1980.

14. Sutton, R.D.; Troth, D.L.; and Miles, G.A.: Analytical Fuel Property Effects on Small Combustors. (EDR-11683 Detroit Diesel Allison Div.; NASA Contract NAS3-23165) NASA CR-174738, 1984.

15. Fletcher, R.S.: Emissions. The Design and Development of Gas Turbine Combustors. Vol. 1, Component Theory and Practice, NREC-1344-1, Northern Research Corp., Woburn, MA, 1980, Chapt. 7.

16. Norgren, C.T.; Mularz, E.J.; and Riddlebaugh, S.M.: Reverse Flow Combustor for Small Gas Turbines with Pressure Atomizing Fuel Injectors. NASA TP-1260, 1978.

17. Tien, J.S.; and Anderson, D.N.: Gas Phase Oxidation Downstream of a Catalytic Combustor. NASA TM-81551, DOE/NASA/1040-16, 1979.

18. Rink, K.K.; and Lefebvre, A.H.: Influence of Fuel Drop Size and Combustor Operating Conditions on Pollutant Emissions. SAE Paper 861541, Oct. 1986.

19. Norgren, C. T.; and Riddlebaugh, S. M.: Small Gas Turbine Combustor Study-Combustor Liner Evaluation. AIAA Paper 83-0337, Jan. 1983 (NASA TM-83028).

20. Spadaccini, L.J.: Low Emission Combustors for Gas Turbine Powerplants. Combust. Sci. Technol., vol. 9, no. 3-4, 1974, p. 133-136.

21. Gordon, S.: Thermodynamic and Transport Combustion Properties of Hydrocarbons with Air. Part 1: Properties in SI Units. NASA TP-1906, 1982.

22. Jones, R.E., et al.: Combustion Gas Properties. I - ASTM Jet A Fuel and Dry Air. NASA TP-2359, 1984.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE I. - ALTERNATIVE TEST FUELS

Fuel	Diesel #2	Gasoline	Methanol	Tar sand DF	100 percent EDS	Hydrogenated EDS	50:50 EDS/DF	77:23 EDS/DF
Southwest identification number	FL0420F	FL0804G	FL0798A	FL0704F	FL0765F	FL1028F	FL0818F	FL1039
NASA program identification, mV	10	60	70	50	20	40	30	90
Density, lb/gal	7.08	6.70	6.95	7.42	7.72	7.59	7.40	7.59
°API gravity	35.1	58.9	46.4	27.5	21.4	23.9	27.9	24.0
Spec gravity at 60° F	0.8493	0.7432	0.790	0.8899	0.9254	0.9106	0.8877	0.9100
Distillation temperatures, °F:								
IBP-5 percent	373-400	77-90	———	338-376	412-424	369-417	382-419	404-418
10-20 percent	417-442	105-133	———	392-426	431-440	424-428	430-440	428-434
30-40 percent	462-481	160-183	———	458-488	449-461	434-442	459-469	439-448
50-60 percent	496-516	203-223	———	517-550	473-489	454-467	485-503	462-477
70-80 percent	537-563	244-272	———	584-621	509-534	479-499	524-551	494-516
90-95 percent	598-625	316-350	———	667-700	573-611	523-557	586-613	542-577
FBP	651	378	———	>763	649	584-636	647	612-649
Recovered, vol %	99.0	97.0	———	99.0	98.0	99.0	99.0	99.0
Residue, vol %	1.0	1.0	———	1.0	2.0	1.0	1.0	1.0
Cetane number	46.5	———	———	34.9	23.5	26.4	34.8	28.5
Cetane index	45.4	———	———	36.0	———	24.8	33.0	26.5
Viscosity, CST at 313 K	2.50	0.46	———	2.91	———	2.34	2.48	2.52
CST at 293 K	-4.0	0.54	———	-4.8	———	———	-4.0	———
Pour point, °F (°C)	1 (-17)	———	———	-44 (-42)	———	-58 (-50)	-18 (-28)	-29 (-34)
Elemental analysis, wt %								
Carbon	86.5	85.48	37.3	87.04	88.50	88.15	87.31	88.39
Hydrogen	12.95	13.36	12.5	11.75	10.90	11.47	12.04	11.35
Sulfur	0.36	0.007	———	0.67	0.01	<0.01	0.16	0.07
Oxygen	———	———	———	———	0.32	0.14	———	0.36
Nitrogen	0.012	———	———	0.028	0.028	0.002	———	0.037
Hydrocarbons, vol %								
Saturates	66.2	59.5	———	32.7	———	37.1	36.9	———
Olefins	1.6	4.6	———	0.0	———	0	0.0	———
Aromatics	32.2	36.4	———	67.3	———	62.9	63.1	———
monocyclic, wt %	———	———	———	10.65	22.46	21.6	———	20.9
dicyclic, wt %	———	———	———	10.18	6.36	3.8	———	6.2
Hydrogen/carbon ratio	1.78	1.85	4.00	1.60	1.48	1.55	1.64	1.53
Net heat, Btu/lb	18 295	18 249	8570	17 934	17 994	17 990	18 008	17 881
Flash point, °F (°C)	148 (70)	-30 (-34)	0	145 (62)	160 (71)	170 (64)	168 (76)	183 (84)
Surface tension, dyn/cm	29.9	20.2	22.6	28.5	29.9	———	29.0	30.9

TABLE II. - TEST PATTERN MATRIX

Fuel-to-air ratio	Input air flowrate, kg/sec			
	0.12	0.23	0.35	0.45
	Input air temperature, K			
0.010	810 950 1090	810 950 1090	810 950 1090	810 950 1090
.012	810 950 1090	810 950 1090	810 950 1090	810 950 1090
.014	810 950 1090	810 950 1090	810 950 1090	810 950 1090
.016	810 950 1090	810 950 1090	810 950 1090	810 950 1090
.018	810 950 1090	810 950 1090	810 950 1090	810 950 1090
.020	810 950 1090	810 950 1090	810 950 1090	810 950 1090

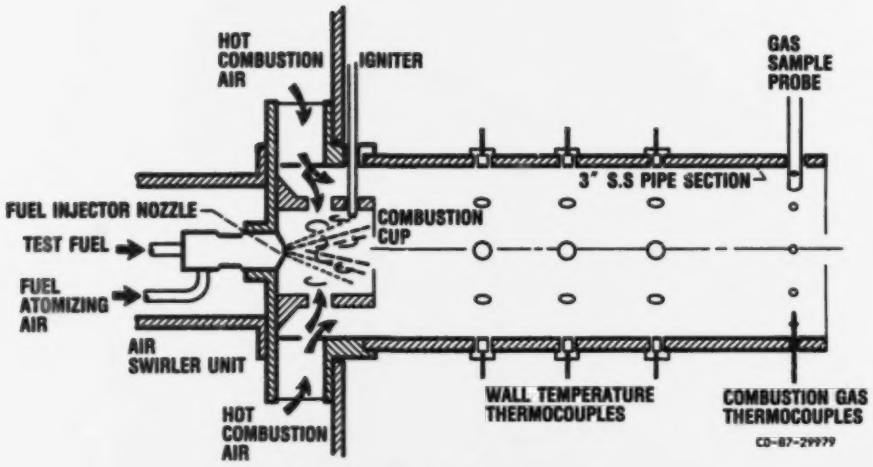


FIGURE 1. - TEST COMBUSTOR CROSS-SECTION.

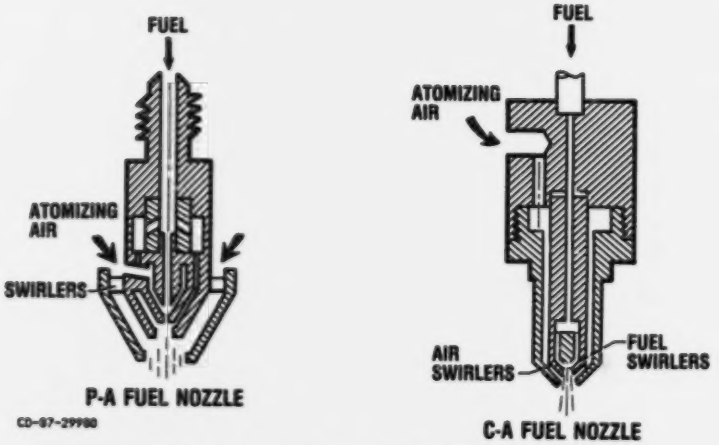


FIGURE 2. - TEST COMBUSTOR FUEL ATOMIZING NOZZLES.

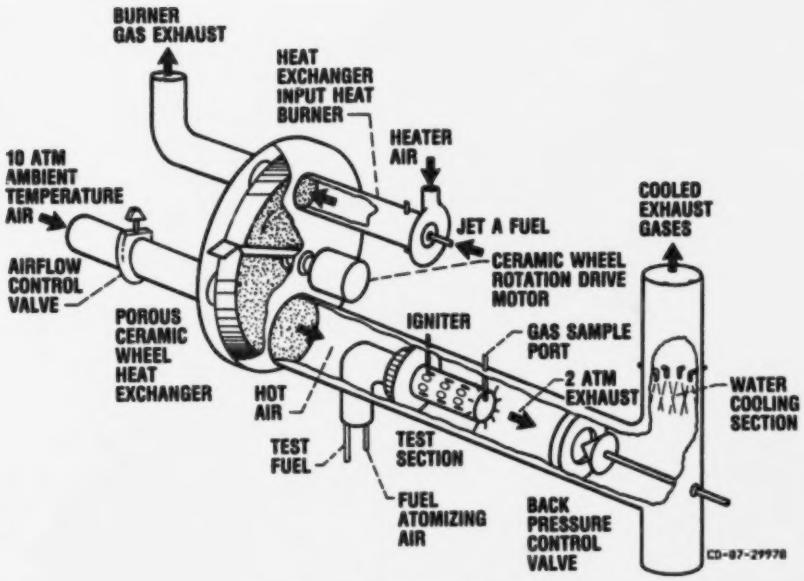


FIGURE 3. - TEST FACILITY SCHEMATIC.

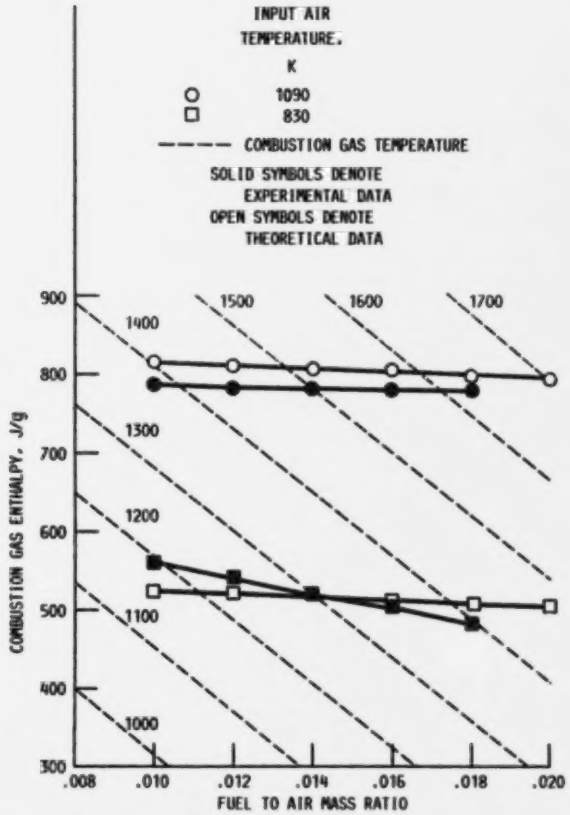


FIGURE 4. - ENERGY LEVEL FOR GASOLINE AND AIR COMBUSTION GASES.

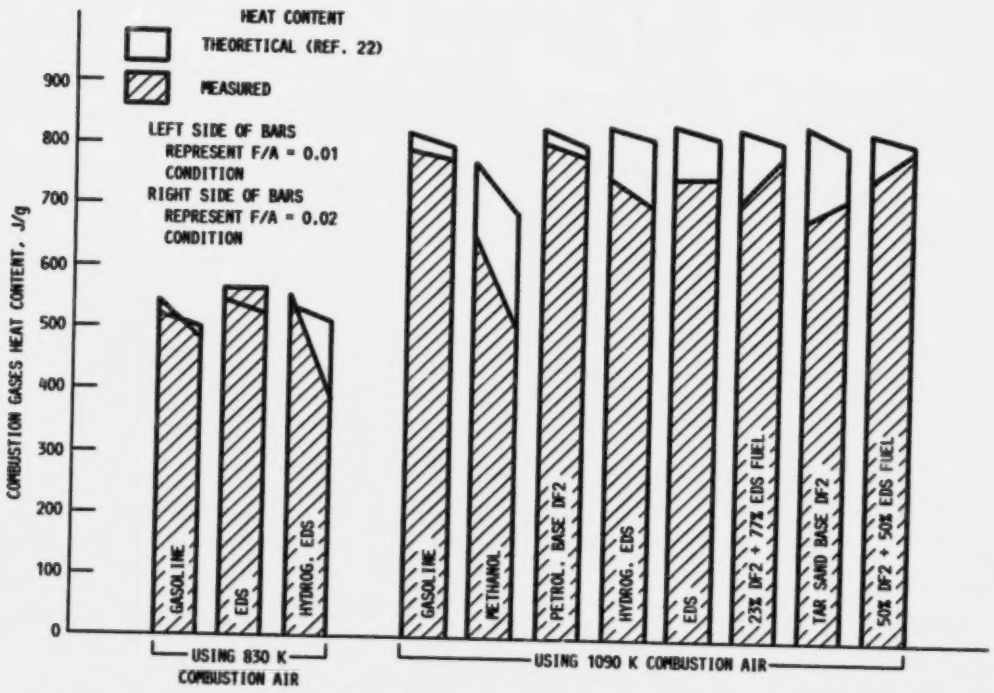


FIGURE 5. - THEORETICAL AND MEASURED HEAT CONTENT (ENTHALPY) OF COMBUSTION GASES FOR DIFFERENT FUELS TESTED. MASS FLOWRATE ≈ 0.3 kg/sec., COMBUSTION PRESSURE ≈ 2 ATM.

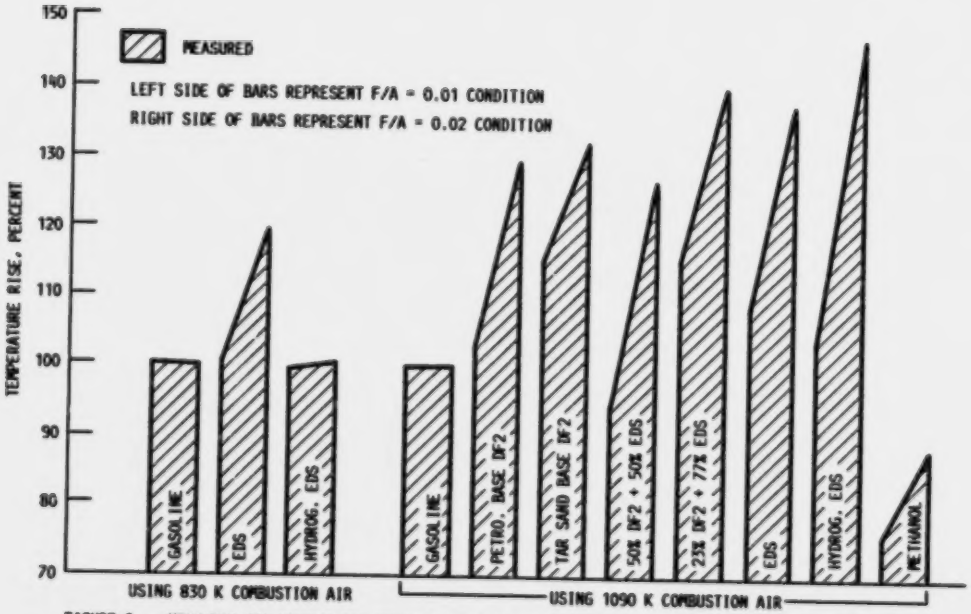
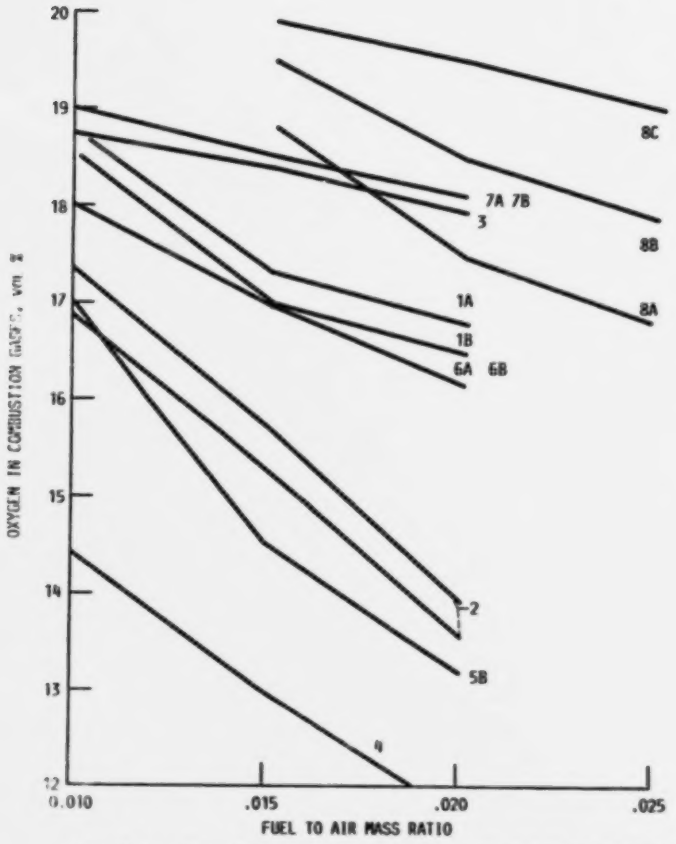
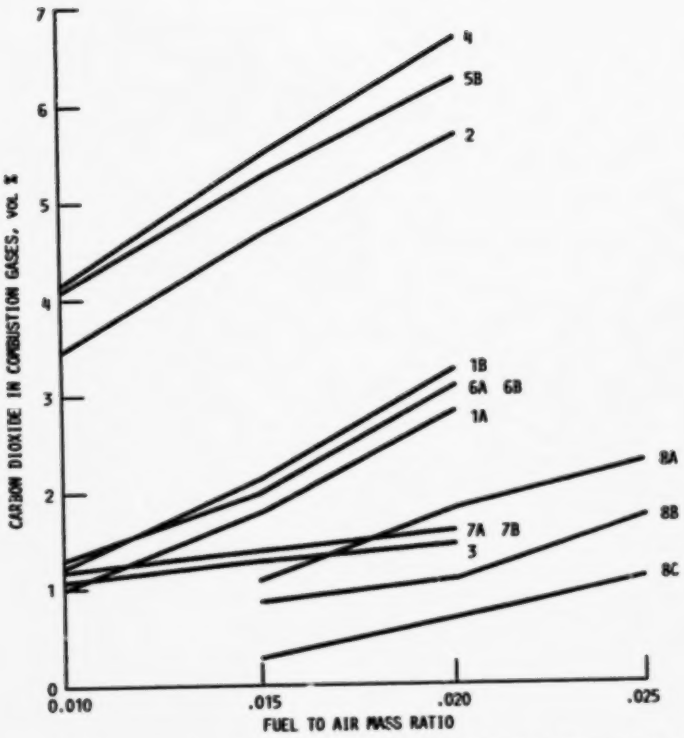


FIGURE 6. - MEASURED COMBUSTION GAS TEMPERATURE RISE OF VARIOUS FUELS AS A PERCENTAGE OF GAS TEMPERATURE RISE WHEN COMBUSTING GASOLINE AT THE SAME OPERATING CONDITIONS AS FUELS.



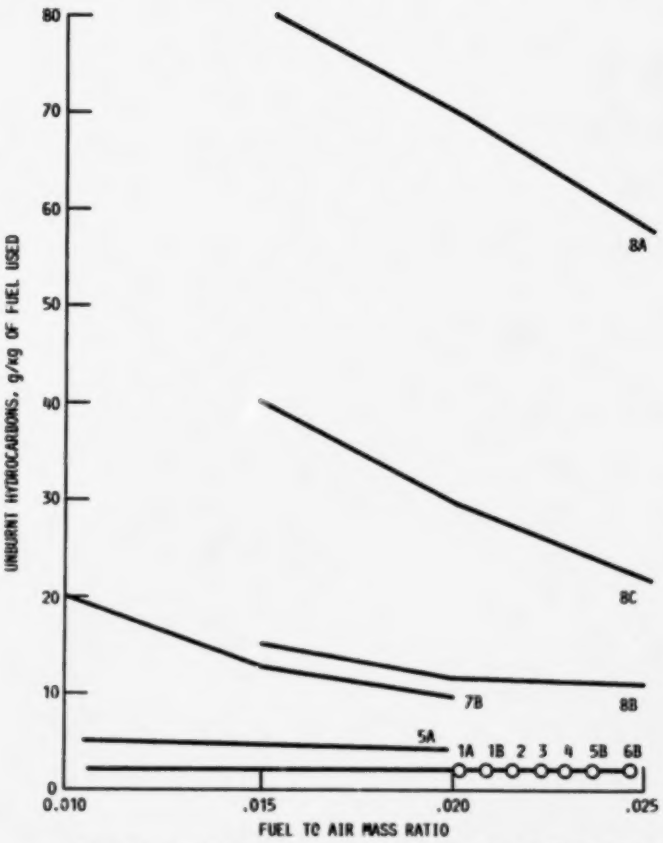
	FUEL	FLOW RATE, kg/sec	AIR TEMPERATURE, K
1A	GASOLINE	0.29	840
1B	GASOLINE	.30	1090
2	TAR SAND DF2	.30	1050
3	PET. BASE DF2	.32	1060
4	50 DF2/50 EDS	.32	1060
5B	23 DF2/77 EDS	.29	1030
6A	PURE EDS	.29	840
6B	PURE EDS	.28	1060
7A	HYDROG. EDS	.29	820
7B	HYDROG. EDS	.29	1060
8A	METHANOL	.16	840
8B	METHANOL	.18	1060
8C	METHANOL	.28	1060

FIGURE 7. - MEASURED VOLUME PERCENT OF OXYGEN IN COMBUSTION GASES AS A FUNCTION OF FUEL TO AIR MASS RATIO FOR EACH FUEL TESTED.



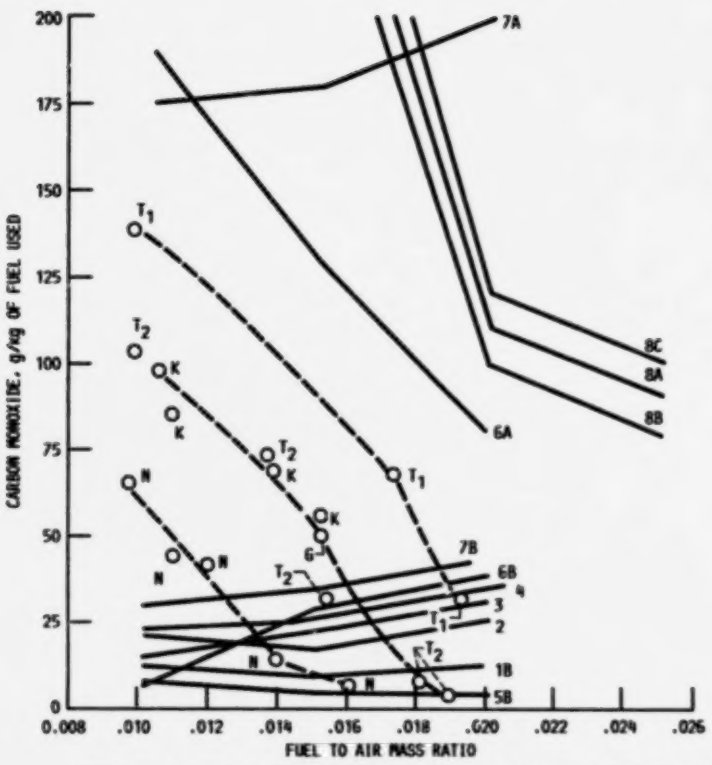
	FUEL	FLOW RATE, kg/sec	AIR TEMPERATURE, K
1A	GASOLINE	0.29	890
1B	GASOLINE	.30	1090
2	TAR SAND DF2	.30	1050
3	PET. BASE DF2	.32	1060
4	50 DF2/50 EDS	.32	1060
5B	23 DF2/77 EDS	.29	1030
6A	PURE EDS	.29	840
6B	PURE EDS	.28	1060
7A	HYDROG. EDS	.29	840
7B	HYDROG. EDS	.29	1060
8A	METHANOL	.16	840
8B	METHANOL	.18	1060
8C	METHANOL	.28	1060

FIGURE 8. - MEASURED VOLUME PERCENT OF CARBON DIOXIDE IN COMBUSTION GASES AS A FUNCTION OF FUEL TO AIR MASS RATIO FOR EACH FUEL TESTED.



	FUEL	FLOW RATE, kg/sec	AIR TEMPERATURE, K
1A	GASOLINE	0.29	840
1B	GASOLINE	.30	1090
2	TAR SAND	.30	1050
3	PET. BASE EDS	.32	1060
4	50 DF2/50 EDS	.32	1060
5A	23 DF2/77 EDS	.28	810
5B	23 DF2/77 EDS	.29	1030
6B	PURE EDS	.28	1060
7B	HYDROG. EDS	.29	1060
8A	METHANOL	.16	840
8B	METHANOL	.18	1060
8C	METHANOL	.28	1060

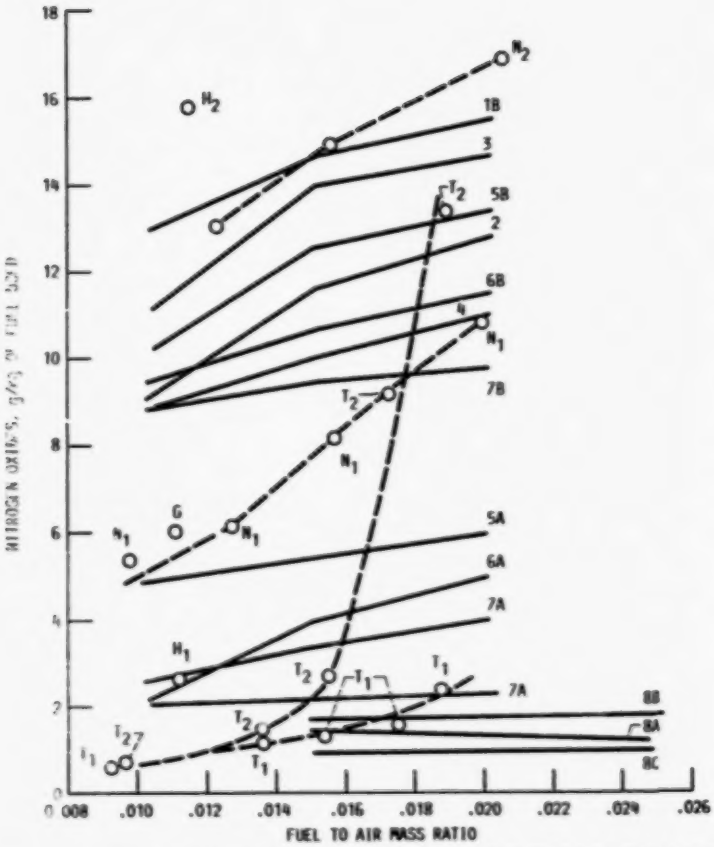
FIGURE 9. - MEASURED CONCENTRATION, EXPRESSED AS AN EMISSION INDEX (g/kg OF FUEL) OF UNREACTED HYDROCARBON SPECIES IN THE COMBUSTION GASES AS A FUNCTION OF FUEL TO AIR MASS RATIO FOR EACH FUEL TESTED.



	FUEL	FLOW RATE, kg/sec	AIR TEMPERATURE, K
1B	GASOLINE	0.30	1090
2	TAR SAND DF2	.30	1050
3	PET. BASE DF2	.32	1060
4	50 DF2/50 EDS	.32	1060
5B	23 DF2/77 EDS	.28	1030
6A	PURE EDS	.29	840
6B	PURE EDS	.28	1060
7A	HYDROG. EDS	.29	820
7B	HYDROG. EDS	.29	1060
8A	METHANOL	.16	840
8B	METHANOL	.18	1060
8C	METHANOL	.28	1060

G	JP4	(REF. 3)
K	JP4	(REF. 13)
N	JP4	(REF. 19)
T_1	DF2	(REF. 14)
T_2	JET A	(REF. 14)
———	REFERENCE TEST DATA	

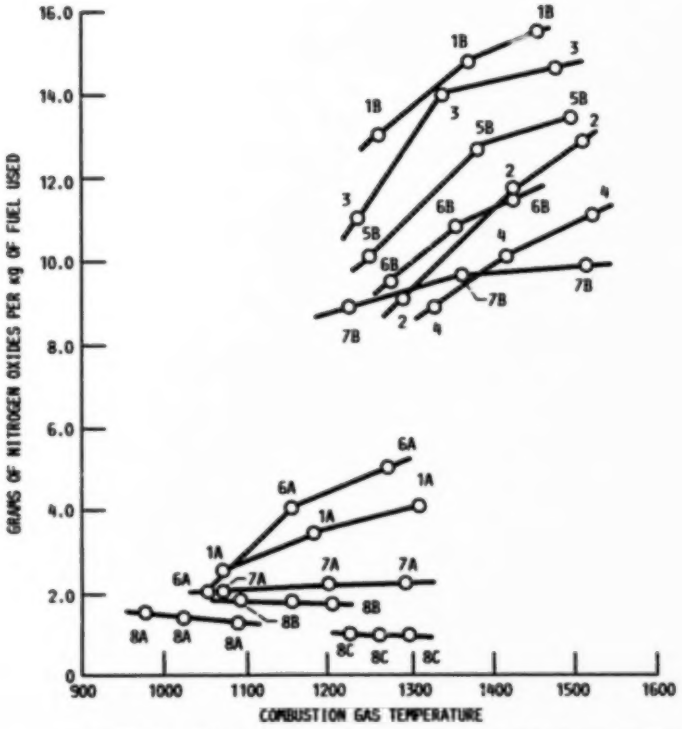
FIGURE 10. - MEASURED CONCENTRATION, EXPRESSED AS AN EMISSION INDEX (g/kg OF FUEL) OF CARBON MONOXIDE IN COMBUSTION GAS AS A FUNCTION OF FUEL TO AIR MASS RATIO FOR EACH FUEL TESTED.



	FUEL	FLOW RATE, kg/sec	AIR TEMPERATURE, K
1A	GASOLINE	0.29	840
1B	GASOLINE	.30	1090
2	TAR SAND DF2	.30	1050
3	PET. BASE DF2	.32	1060
4	50 DF2/50 EDS	.32	1060
5A	23 DF2/77 EDS	.28	810
5B	23 DF2/77 EDS	.29	1030
6A	PURE EDS	.29	840
6B	PURE EDS	.28	1060
7A	HYDROG. EDS	.29	820
7B	HYDROG. EDS	.29	1060
8A	METHANOL	.16	840
8B	METHANOL	.18	1060
8C	METHANOL	.28	1060

G	JP4	(REF. 3)
H_1	METHANOL	(REF. 4)
H_2	JET A	(REF. 4)
N_1	JET A	(REF. 16)
N_2	JP4	(REF. 19)
T_1	DF2	(REF. 14)
T_2	JET A	(REF. 14)
———	REFERENCE TEST DATA	

FIGURE 11. - MEASURED CONCENTRATION, EXPRESSED AS AN EMISSION INDEX (g/kg OF FUEL) OF NITROGEN OXIDES IN COMBUSTION GASES AS A FUNCTION OF FUEL TO AIR MASS RATIO FOR EACH OF THE GASES TESTED.



	FUEL	FLOW RATE, kg/sec	AIR TEMPERATURE, K
1A	GASOLINE	0.29	840
1B	GASOLINE	.30	1090
2	TAR SAND DF2	.30	1050
3	PET. BASE DF2	.32	1060
4	50 DF2/50 EDS	.32	1060
5B	23 DF2/77 EDS	.28	1030
6A	PURE EDS	.29	840
6B	PURE EDS	.28	1060
7A	HYDROG. EDS	.29	820
7B	HYDROG. EDS	.29	1060
8A	METHANOL	.16	840
8B	METHANOL	.18	1060
8C	METHANOL	.28	1060

FIGURE 12. - MEASURED CONCENTRATION, EXPRESSED AS AN EMISSION INDEX (g/kg OF FUEL) OF NITROGEN OXIDES IN COMBUSTION GASES AS A FUNCTION OF COMBUSTION GAS TEMPERATUE OBTAINED WITH EACH FUEL TESTED.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-101470 DOE/NASA/50111-3		

4. Title and Subtitle	5. Report Date
Gas Turbine Alternative Fuels Combustion Characteristics	February 1989
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
R. James Rollbuhler	E-4584
	10. Work Unit No.
	778-32-11

9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
	Technical Memorandum

12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
U.S. Department of Energy Office of Transportation Systems Washington, D.C. 20545	

15. Supplementary Notes

Final Report. Prepared under Interagency Agreement DE-AI01-85CE50111.

16. Abstract

An experimental investigation was conducted to obtain combustion performance and exhaust pollutant concentrations for specific synthetic hydrocarbon fuels. Baseline comparison fuels used were gasoline and diesel fuel number two. Testing was done over a range of fuel to air mass ratios, total mass flow rates, and input combustion air temperatures in a flame-tube-type gas turbine combustor. Test results were obtained in terms of released heat and combustion gas emission values. The results were comparable to those obtained with the base fuels with variations being obtained with changing operating conditions. The release of carbon particles during the tests was minimal.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Alternative fuels; Petroleum; Oil shale; Coal; Alcohol; Hydrogen; Gas turbine; Fuel properties; Combustion properties	Unclassified – Unlimited Subject Category 44 DOE Category UC-96

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	24	A03

*For sale by the National Technical Information Service, Springfield, Virginia 22161